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Accurate Polarization Dependent Loss Measurement and Calibration Standard Development

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Abstract - We have implemented an automated, nonmechanical approach to the measurement of polarization dependent loss. We use a deterministic fixed-states method to obtain Mueller matrix elements from intensity measurements at specific polarization states. Voltage-modulated liquid-crystal variable retarders set the input polarization states. Synchronous detection is employed to increase the signal-to-noise ratio of the system and thereby allow a measurement resolution of better than 0.001 dB. We present polarization-dependent loss measurements from 0.0016 to 0.56 dB at 1550 nm to verify performance. We also present results from potential artifact calibration standards of an all-fiber design.

Introduction

Polarization dependent loss (PDL) is defined as $10\log(T_{max}/T_{min})$ (dB) where T is transmittance taken over the entire polarization-state space. Polarization dependent loss is usually characterized as a localized component effect as opposed to the distributed nature of polarization mode dispersion. PDL measurement methods can be divided into three categories, all of which are represented by commercial instrumentation: deterministic fixed-states, deterministic all-states, and pseudorandom all-states [1]. We have implemented a deterministic fixed-states technique. Our goal is to establish the capability to measure PDL with a resolution finer than 0.001 dB and to determine the absolute accuracy of our method. In this paper we summarize an approach to polarization dependent loss measurement that employs a nonmechanical technique capable of synchronous detection. This system has been described more fully in [2]. We also present new results from an all-fiber PDL artifact reference that is potentially useful as a transfer standard. This may lead to a Standard Reference Material for the calibration of commercial instrumentation.

Because PDL is always greater than or equal to zero, noise in the PDL measurement system can degrade the sensitivity to very small PDL values (where the PDL is less than the system's single-measurement noise). Sensitivity to these small PDL values cannot be improved by increasing the number of measurements; the average of multiple PDL measurements will always yield a positive value that is proportional to the single-measurement noise. However, synchronously averaging measured intensities in a deterministic fixed-states method can improve sensitivity due to the increase in the signal-to-noise ratio.

We implemented our system using voltage-modulated liquid-crystal variable retarders (LCVR) and synchronous detection. A different LCVR approach has also been reported [3]. However, in our case, modulation of the polarization state allows differential measurement as well as an improvement in sensitivity due to synchronous time averaging.

Concept

Our method, which we call the Mueller-Stokes technique, is a variation on a matrix technique developed by Favin et al. [4], and relies solely on power measurements at specific polarization states. In this deterministic fixed-states method, four well-defined polarization states are necessary to determine the first-row Mueller matrix elements of a component. The global polarization dependence of transmittance can then be determined from these four elements.

Because the measurement depends only on the relative coordinates of the four states, the only requirements on the set are that they maintain relative angular separations of 90° about the origin of the polarization (Poincaré) sphere. This implies that constant intervening retardance, as represented by rotations of the sphere, will have no net effect. A representative sample of states is shown in Fig. 1a, while a rotation of those states is

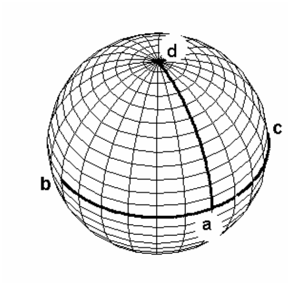

Figure 1a: Initial Poincaré trajectories of the LCVR pair over a measurement.

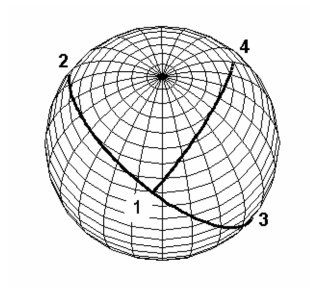

Figure 1b: LCVR trajectories following birefringent displacement

seen in Fig. 1b.

In our system, the polarization states are produced by two LCVR units in series. These modulate the polarization state of a low-coherence polarized beam. The effect of the pair is to produce final polarization states equivalent to those produced by a quarter-wave and half-wave retarder combination undergoing independent rotations. Following generation of the four polarization states (with average powers I_a, …, I_d), the light is transmitted by a single mode fiber with arbitrary but relatively stable birefringence through the device under test (DUT). It proceeds to a polarization-insensitive detector which measures the four time-averaged output powers (I_1, …, I_4). We measure the time-averaged input powers (I_a, …, I_d) in the same way with the DUT removed to establish a baseline system response. The four first-row Mueller matrix elements (m_{11},…, m_{14}) are combinations of ratios of these powers [2]. Information about the global transmittance extrema are contained in the first row matrix elements. The transmittance extrema, T_{min} and T_{max}, are

$$T_{\max} = m_{11} + \sqrt{m_{12} + m_{13} + m_{14}} \ ,$$

$$T_{\min} = m_{11} - \sqrt{m_{12} + m_{13} + m_{14}} \ . \qquad (1)$$

Polarization dependent loss then follows as defined above.

The essential advantage of this technique is nonmechanical retardance modulation, which allows rapid synchronous time averaging in a low noise environment at a frequency set by an external clock. Synchronous time averaging improves the signal-to-noise ratio and can be applied in different ways depending on the method of signal acquisition chosen.

Implementation

Figure 2 shows a schematic of the measurement system. Our system consists of five major sections: source, LCVR cavity, detector, boxcar averager and control computer. We connect the polarization-modulated light directly to the DUT without any intervening components other than single-mode fiber and fiber connectors. Measurements at each polarization state are

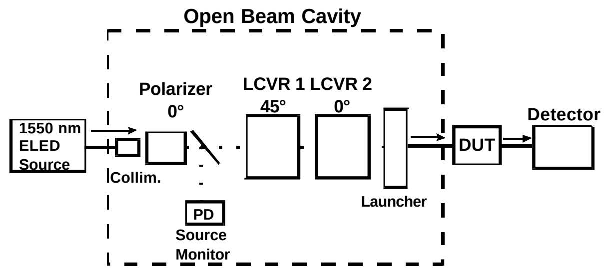

Figure 2: Simplified block diagram of the LCVR PDL measurement system.

limited to a fixed number N of modulation cycles at clock frequencies of 3.5 Hz to 10 Hz. Each of the three congruent line segments in Fig. 1 originating from the vertex represents the modulation path between two Mueller-Stokes states and therefore a signal to be sampled. This signal is routed to two averager channels, and each channel has a delay set to position the respective gates on alternate periods. To the extent that we can control birefringence drift during the sampling of each polarization state, resolution increases as $\sqrt{N}$. In addition, we use differential measurements to eliminate common-mode drift. To obtain the proper Stokes powers, each of the three difference measurements must be subtracted from the absolute power of the central polarization state. We measure the central state power by chopping the source at the clock frequency.

Uncertainties

A detailed analysis of the uncertainties in our PDL measurement system shows several dominant uncertainty sources. We list them in order of decreasing importance. Values listed correspond to one standard uncertainty (1σ) about the signal power I_{sig}.

Polarization state uncertainty. Polarization state accuracy depends on the accuracy of the calibrating polarimeter as given by the manufacturer. Value: ±0.83% of I_{sig}.

Retarder temperature dependence. We quantify temperature dependence primarily in terms of its effect on the LCVR elements. A worst-case temperature variation of 0.5 °C is used to derive the uncertainty in signal power due to variation in the polarization state of ±0.2%. Value: ±0.12% of I_{sig}

System internal PDL variation. The system retardance elements contribute their own PDL (0.02 dB) to that of the DUT. If this value is constant during both phases of the measurement, it is cancelled in the ratios. Our quoted PDL variation was derived from the maximum observed slope of the internal PDL over 15 minute intervals. Value: ±0.12% of I_{sig}.

Propagated measurement system uncertainty. We have propagated the uncertainties above inherent to the measurement system in a model of the nonideal system. The combined total PDL deviations are then calculated from the defining equations [2] to be ±2.1%. Value: ±2.1% of PDL.

PDL measurement repeatability. The repeatability given is one standard deviation (1σ) of repeated undisturbed measurements following the initial baseline measurement. By undisturbed, we mean that one sample follows another with no connector disconnection in between. This value is the effective system noise. Value: ±0.0008 dB.

Combined standard uncertainty. The effects are assumed uncorrelated, so we combine the above results using the root-sum-of-squares (RSS) method as (±0.0008 dB & 2.1% of PDL) RSS.

A significant source of uncertainty, which was not inherent to the LCVR system, was variations in measured PDL of DUT artifacts with connectorized pigtails following disconnection and reconnection. This could be explained by connector alignment errors. For those artifacts we add an additional ±0.0029 dB uncertainty. In our system, we took care to minimize fiber motion during connector handling. However, if this is not done, one could introduce errors from alterations in the relative orientations of system, DUT, and connector PDL axes due to shifts in pigtail birefringence

Stability in system birefringence is important both during and between each set of power measurements in any fixed-states scheme. Large intermediate instabilities or drifts could lead to significant uncertainty. While the effects can be modeled, it is best to simply minimize the instability. An advantage of our technique is that measurements can be performed quickly, so the stability criterion is easily satisfied.

We compared measurements between the fixed-states technique and the commonly used polarization-scanning (or all-states) method. The all-states technique relies on pseudorandom sampling of all polarization states with a total uncertainty that is proportionally reduced by increasing measurement time and/or scanning speed. For PDL ≤ 0.1 dB, uncertainties in the range of ± 3% to ±5% of PDL are claimed for a 30 second measurement [5].

Results

The primary artifact chosen to test the performance of the system provides a calculable PDL of moderate accuracy. It consists of an open beam launcher/collimator (a cleaved section of single-mode fiber and objective lens) followed by a polished BK7 glass cube. We mount the cube on a rotation stage with 5' resolution. The InGaAs detector (which includes a ceramic depolarizer) is translated to compensate for beam displacement following rotation. Calculated PDL (Fresnel) and measured (Mueller-Stokes) values as a function of input angle are presented in Fig. 3 and are in good agreement. Our residual system PDL was measured and accounted for as a 0.0016 ± 0.0001 dB offset at normal incidence, where the uncertainty quoted is the statistical uncertainty of the mean with 95% confidence interval ($2\sigma/\sqrt{N}$). This nominally left only the dual glass/air interfaces to produce PDL.

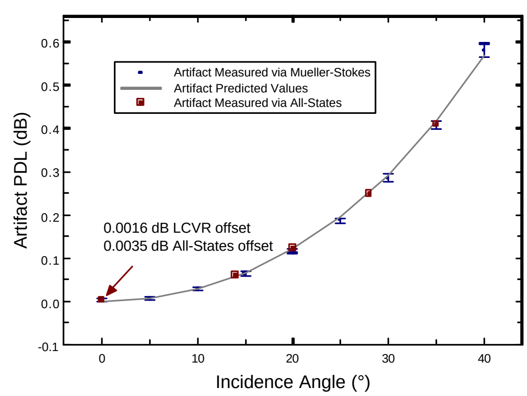

Figure 3: Open-beam artifact data from both the Mueller-Stokes and all-states systems. Error bars represent total uncertainty. The solid line is the calculated PDL value.

To test the measurement resolution, a series of Mueller-Stokes measurements were performed by alternating between 15° and 15°5' and measuring the PDL difference. We found the average of those measurements, 0.0008 ±0.0003 dB, to be in good agreement with the predicted value.

All-Fiber PDL Artifact

We have constructed a series of all-fiber PDL artifacts based on fusion-spliced sections of single-mode, polarizing, and multimode fiber as shown in Fig. 4. These artifacts show promise for use as calibration transfer standards. We use hot-wire splicing to produce clean joints between dissimilar fibers. The input is a short single-mode section for accurate coupling to system leads. The artifact section is a few millimeters of polarizing fiber (18 dB/m rejected mode extinction) that provides stable PDL. We have generated PDL in the range of 0.063 to 0.230 dB with lengths of 5 to 17 mm, where PDL increases with polarizing fiber length. Splices can modify artifact behavior, possibly by introducing additional PDL or changing the rejected-mode extinction. The output section is composed of several meters of multimode fiber to minimize losses due to aperture mismatch and depolarize the signal, thereby reducing uncertainty due to detector PDL. These artifacts provide good temperature stability over the range of 0 to 40 °C. We have measured a PDL temperature dependence of -0.00015 dB/°C for a 10 mm artifact with 0.085 dB of mean PDL and a dependence of -0.001 dB/°C for a 17 mm artifact with 0.230 dB of mean PDL. These artifacts are suitable both for fusion splicing as well as connectorizing the input lead.

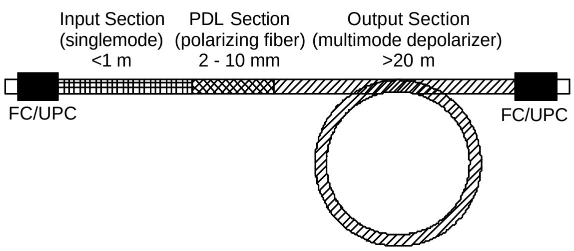

Figure 4: Schematic of the prototype all-fiber PDL artifact.

Conclusions

We developed a nonmechanical technique of polarization dependent transmittance measurement for both single-mode and bulk-optic devices that offers advantages over more traditional methods. The technique is capable of synchronous time averaging, which allows resolution of better than 0.001 dB and agreement within 0.0016 dB ±2% of PDL values calculated for an open-beam artifact. The accuracy can be improved in the future by improving the accuracy of the polarization state calibration.

A new PDL artifact standard candidate is proposed. Measurements of the temperature dependence of prototypes show PDL slopes as low as 0.00015 dB/°C over the temperature range 0 to 40 °C.

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